V.

HIGH ELECTROMOTIVE FORCE

ITS APPLICATION TO THE STUDY OF POWERFUL ELECTRICAL DISCHARGES AND TO SPECTRUM ANALYSIS.

BY

JOHN TROWBRIDGE.

WITH PLATES XXV – XXVII

PRESENTED MARCH 13, 1907. RECEIVED MARCH 5, 1907.

INVESTIGATIONS ON LIGHT AND HEAT MADE OR PUBLISHED, WHOLLY OR IN PART, WITH APPROPRIATIONS FROM THE RUMFORD FUND

CONTENTS.

HIGH ELECTROMOTIVE FORCE.

DESCRIPTION OF THE BATTERY.

THE appliances for research have greatly increased since the time of Faraday; but it is significant that the wealth of means has not contributed much to our knowledge of the science of electricity. The advances have come from workers who have not had at their command very powerful electrical currents, such as are used in commercial applications; and I am led to conclude that the best equipment of a physical laboratory resides in good minds and not in elaborate installations and large collections of physical apparatus.

Nevertheless a step is made when the limits of application of the present powerful sources of electricity can be shown in such a subject, for instance, as Spectrum Analysis.

Thirty years ago investigators depended upon voltaic batteries for their source of electric currents. The limits of electromotive force were necessarily low, on account of the expense involved in a plant of a large number of cells, and the labor of setting up the cells was very great. In the literature of electricity and magnetism one finds a full account of the large experimental battery of de la Rue and Müller. This consisted of 8040 elements of amalgamated zinc and chloride of silver in a salt or sal ammoniac solution. Each cell consisted of a glass tube 15.23 cm. long and 1.9 cm. in diameter. The tube was closed by a rubber stopper to avoid evaporation: the chloride of silver paste and a strip of silver constituted the positive pole of the cell. This silver strip was carefully protected from the sulphur of the rubber stopper by suitable insulation. The electromotive force of each element was 1.03 volts and the internal resistance of each cell 38.5 ohms. The total electromotive force of the battery was approximately 8281.2 volts. De la Rue and Müller recommend such an installation for use in spectrum analysis.

Before entering upon a more detailed account of a much larger installation I will give here, for comparison, similar data in regard to this installation.

The cells of the battery in the Jefferson Physical Laboratory number 20,000; the glass tubes of each cell are 14 cm. long, 1.9 cm. in diameter, — not differing therefore much in size from the de la Rue and Müller battery. The electromotive force of

each cell is approximately 2 volts and the internal resistance 1.50 volts; the total electromotive force of the battery is 40,000 volts. It can produce in air an initial spark of 3.5 cm. to 4 cm., and when the terminals are quickly drawn apart, a flaming discharge of 60 cm.

This modern large installation has been made possible by the discovery of the Planté accumulator, which enables one to utilize the powerful currents generated by the dynamo machine to polarize lead plates and thus to dispense with voltaic cells. The latter have entirely disappeared from physical laboratories except for minor purposes, such as call bells; and the three or four hundred Bunsen or Grove cells which were once used in lectures on physics have been thrown into the scrap heap.

I published in the Proceedings of the American Academy, Vol. XXXII, p. 253, also Vol. XXXIII, p. 435, a description of this battery, which I had constructed for the purpose of studying the spectra of hydrogen, especially the new series of hydrogen lines discovered by Professor E. C. Pickering in the spectrum of certain stars. It was hoped that under conditions of high electromotive force and strong currents this new series might be reproduced in a laboratory. Although this hope was found to be fallacious, the installation of such a large plant has proved extremely useful where a steady electric field is necessary.[1] It has shown that spectrum analysis of rarefied gases is practically limited to comparatively small electromotive forces and weak currents. An experience of twelve years in the use of the battery impels me to gather in a memoir the results of my experience. The life of the battery as it was originally constructed has been ten years, and the improvements I shall describe in this memoir will, I believe, greatly extend its life.

The form of cells which I adopted, consisting of test tubes enclosing strips of lead formed by the Planté method, is undoubtedly the cheapest and most compact form that can be selected. A less number of cells, of larger size and of the pasted type, might be more enduring; but they would occupy a much greater space and would be far more expensive.

The battery with which I have experimented requires a room $20 \times 30 \times 14$ feet. It is contained in eight cabinets or cases. The space occupied by the battery could be lessened by a more compact arrangement of the trays which hold the cells.

Each of the unit trays consists of three compartments (Figure 1, Plate XXV), and holds sixty cells. The supports of the test tubes are made of kiln-dried whitewood soaked in paraffine. The tubes rest on a lower shelf, and are held upright in holes in an upper shelf. The individual trays, comprising together what I have termed a unit,

[1] H. L. Blackwell, Proc. Am. Acad., Vol. XLI, No. 32.

are placed side by side with an air space between them, and are kept apart by glass or porcelain tubes.

It is necessary that the cells of each tray should be connected with lead wire, and that the connection between these lead wires and the switches, together with the copper conductors of the exterior circuit, should be far removed from the cells. When the battery was first installed, these connecting lead wires were led through glass tubes in the wood partitions separating the trays. It was soon found, however, that the sulphuric acid crept along the lead connecting wires, a distance of eight to ten inches from the cells, covering the glass conduits and soaking into the wood partitions, thus short-circuiting the cells. Accordingly the glass tubes were removed and the lead wires were led through air spaces. This disposition remedied the difficulty. My experience with various insulating material has taught me that dry air is the best insulator that one can obtain at moderate expense; and next to it is kiln-dried wood soaked in paraffine. The latter, however, must not be exposed to acid fumes.

The scheme of electrical switches for this experimental plant has been the subject of much thought. It was desirable that a range of voltage extending from the contents of one of the unit trays — 60 cells, approximately 120 volts — through all the multiples of this unit up to 40,000 volts, could be obtained. At first the cells were charged in multiple with a current of 60 volts, the cells being arranged in multiple, 20 cells in each derived circuit, the charging current through each cell being one-thirtieth of an ampere.

The switchboards are placed on the back of each of the unit cabinets, there being eight of these cabinets. The switches are three point switches (Figure 2, Plate XXV). When they are thrown to the right, the batteries are in multiple for charging; when thrown to the left, the cells are in series. An entirely similar switchboard serves to throw each cabinet into multiple or tandem.

It is evident that with a charging current of only 60 volts a large number of switches are necessary. The following arrangement, suggested to me by Dr. H. W. Blackwell, who has studied the disposition of the cells for use in his work on electric double refraction, has greatly simplified the arrangement of switches, and lessened the work of throwing the cells from multiple to series:

A charging current of 500 volts is now used. The cells in each cabinet are arranged in multiple, 60 in each shelf, $3\frac{1}{2}$ shelves, or 420 volts. This change merely requires throwing a one point switch on the switchboard, the cells remaining in series, and being divided at a middle point, giving 210 cells in each derived branch. With a suitable transformer and a mercury rectifier it is evident that the number of switches

and switchboards could be further reduced. The danger in using the batteries evidently increases with the number of switches which must be manipulated. This danger is very great, for 20,000 cells, even of the small test tube type, can yield for a few seconds a current of eight amperes at 40,000 volts. In using the batteries one is speedily convinced that a steady current of large amperage at voltages as low as 200 can be dangerous to life. The amperage is just as important a factor as electromotive force in considering this danger.

Figure 2, Plate XXV, shows the arrangement of connections and switches on the back of each compartment of the battery. There are 48 compartments. In each compartment there are 7 shelves, 60 cells to each shelf; thus 420 cells, or 820 volts, to a compartment. These cells are connected to the line for charging or discharging by the switches S. When these switches are thrown to the right hand of one facing the switchboard, the cells of each shelf are connected in series up to switches $S_4 S_4$. At this point $3\frac{1}{2}$ shelves are put in multiple; that is, 210 cells, or 420 volts. The charging current of 500 volts thus has to overcome this difference of potential. All of the switches S to $S_4 S_4$ are thrown to the right, both in charging and discharging. To discharge it is only necessary to throw switch S_5 to the left, thus putting all the cells in series. The time necessary to throw the cells from charging to discharging is ten minutes. From two to three hours of charging with a voltage of 500 and a current of two amperes is generally necessary to bring the cells up to working voltage. As in the case of all lead accumulators or storage batteries, a transient or pseudo voltage, if the cells are not fully charged, is shown, which quickly disappears in connecting the terminals of the cells.

One of the chief causes of the deterioration of an accumulator is the buckling of the plates due to overdischarging. This buckling causes the positive and negative plates to touch, and thus to short-circuit the cells. This buckling can readily happen unless the plates are massive, or held apart rigidly. Massive plates add much to the weight of the cells, and when a large number are needed for great electromotive force the weight is prohibitive. The plates are 1.2 cm. broad, 14 cm. long, and are approximately 1 mm. thick, weighing approximately one-sixteenth of a pound. They are roughened deeply by a suitable die.

At first I adopted the expedient of keeping the plates apart by means of rubber bands. Experience, however, has shown that this is a very temporary expedient, for the rubber disintegrates, and also becomes covered in time with the active material which falls from the plates; they then serve as conductors to short-circuit the cells. In a new arrangement of the cells I have dispensed with the rubber separators and

use wood separators; these wood separators are somewhat broader than the lead plates and a centimeter longer. They reach to the bottom of the glass containing tube, while the lead plates are lifted from the bottom of these tubes about a centimeter. The active material, therefore, which might fall to the bottom of the cells cannot short-circuit the cells. The separators consist of strips of wood 1 mm. thick. When they are saturated with the dilute acid, they do not oppose any appreciable resistance. The use of wood separators in storage cells was discovered by Mr. E. P. Usher in a remarkable installation at Milford, Mass., which served as the source of electric power for trolley cars on the route between Milford and Hopedale. Mr. Usher was the first to show that they did not oppose any appreciable resistance, and that they prevented the trouble of buckling. With the employment of these wood separators the experimental battery which I describe in this memoir can be short-circuited without danger to the battery.

Figure 1, Plate XXV, shows one tray of the battery with wood separators extending to the bottom of the tubes. Lead wires connect the plates of the cells to the switches on the back of the compartments which hold the cells. These wires extend from each row of cells to the switches connecting the rows of cells, a distance of, approximately, 50 cm. It was found necessary that these lead wires should rise vertically from the cells through a distance of 4 or 5 cm., in order that the acid solution in the cells which creeps up the wire should drain back into the cells instead of dripping upon the wooden supports of the cells. These lead wires do not touch the woodwork at any point, and do not rest upon any insulators save two porcelain insulators which are directly above the end cells on each shelf. It was found, as I have said, that if they were led through glass tubes inserted in wood, the glass in time became covered with an acid solution which was communicated to the wood in which the glass tubes were inserted, and the wood thus became conducting. The liquid in the cells, dilute sulphuric acid, is covered with a thin layer of paraffine oil to prevent evaporation. The acid solution is renewed about once in three months to replace the loss due to this evaporation. The lead plates in the course of two or three years become friable, having become almost entirely converted into active material, and therefore need to be replaced. This replacement, of course, depends upon the use of the battery. Thicker plates would lengthen the life of the cells, but would also lead to greater weight.

An open construction of each compartment of the battery is desirable, in order that the condition of the cells can be easily seen by passing an incandescent lamp behind the rows of cells. This open construction is shown in Figure 3, Plate XXV. It

will be seen from Figure 1, Plate XXV, that each tray of cells rests upon porcelain insulators at their ends and at their middle. The wood between the rows of cells is removed, leaving a slot; the only wood connection is therefore at the ends of the trays.

LEAKAGE TO GROUND AND SIDE DISCHARGES.

The installation of such a large storage battery as I describe in this memoir presents many interesting problems of insulation, and it is probable that with the most perfect insulation possible there is an invisible ionization between the cells and the earth.

Such ionization becomes visible in the form of the Geissler tube shown in Figure *A*. The terminal A is connected permanently with the pole of the battery through a large running water resistance of several megohms; the terminal B is connected to the negative pole by a spark gap. E E are condensers connected to the earth. At the instant the spark occurs, a brilliant side discharge occurs between E and A. At the same time that these side discharges take place, a discharge passes between A and B. It is evident that the capacity of the region outside the battery, the room and building, charges up under the difference of potential between it and the poles of the battery, a difference of potential which is greater than that between A and B which are connected by the small resistance of the rarefied gas.

This phenomenon suggests a photometric method of comparing the capacity of large condensers and also of obtaining the capacity of the surrounding space. To the arms C and D of the cross are attached the condensers to be compared. At the instant of completion of the circuit with the storage battery under the conditions mentioned above, two side discharges take place from C and D, either to A or B. By bringing the light of these two simultaneous discharges into a suitable photometric arrangement, one can compare the capacities of the condensers to the degree of accuracy obtainable by ordinary photometric observations. Since it is difficult to obtain an estimate of the capacity of large bodies of irregular shape and of large extent, this method may be of use. By a suitable vacuum tube and proper exhaustion the method does not require a large number of cells.

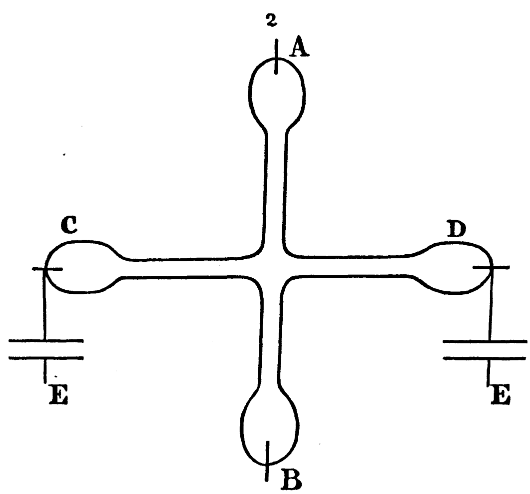

FIGURE *A*.

It was noticeable that when a stratified discharge was established between A and B, there being no spark gap in the circuit except that of the rarefied space between A and B, fluctuating feeble discharges took place to earth through E. This phenomenon seems to indicate a discontinuity in the stratified discharge.

When the small spark gap, either at the positive or negative pole, is of a suitable length, the discharges between either pole of the battery succeed each other so rapidly that the side discharges to earth appear continuous. If a large condenser is substituted for the earth at E, one plate of the condenser being connected to earth, the time between each discharge is lengthened.

It is probable that in the case of lightning side discharges to the earth take place in the manner indicated by this method; the potential between the positively and negatively charged clouds rising to a higher value than that between the clouds, the earth space beneath the clouds acting as a localized capacity.

FLAME, IONIZATION AND ELECTRICAL WIND.

By the use of the wooden separators, as I have said, one can short-circuit the cells without fear of permanent injury. In doing this, several interesting phenomena appear. In a dark room a faint glow is always seen on the negative terminal of ten thousand cells. This glow is independent of the position of the positive terminal, and is an evidence of a silent discharge or ionization. On the other hand, a glow at the positive terminal does not appear (with a difference of potential of 20,000 volts) until this terminal approaches to a distance of 17.5 cm. from the negative terminal, both terminals being pointed. After the positive terminal is brought to a distance of 4 or 5 cm. from the negative terminal, — that is, to near the striking distance, — and is then drawn away, the glow on the positive terminal persists to a greater distance than that at which it is just discernible. This is shown in the accompanying table.

First appearance of the glow on the positive terminal.	Glow can be drawn to
17.5 cm.	20.5 cm.
16	20
17.5	20

This phenomenon is analogous to the persistence of the flaring discharge which occurs when the terminals are brought within striking distance and then are drawn apart. This flaring discharge extends to a distance of 60 cm. (with 40,000 volts). I then endeavored to see whether in an unsymmetrical field in air one finds a phenomenon analogous to the Faraday column which extends in the similar unsymmetrical

field of Geisler tubes from the positive terminal to approximately two-thirds of the distance between the pointed terminals in the tube.

A candle flame, therefore, was placed on the line between pointed terminals. These terminals were then moved toward each other until the effect upon the flame was symmetrical; that is, when the flame assumed a flattened shape somewhat like an egg resting on its smaller end. It was then found that the distance of the negative terminal from the centre of the flame was 5 cm., and the distance of the positive terminal 10 cm. It seems, therefore, that even at atmospheric pressure something analogous to the Faraday column begins to manifest itself. In a Geisler tube at suitable pressure, as is well known, this column is steadily driven back from the cathode space as the vacuum rises.

In general experiments on the effect of an electrical field on the flame of a candle with a symmetrical field, I obtain with the terminals of an accumulator of 20,000 volts the results of previous observers who worked with electrical machines.[1]

With pointed terminals it is very evident that the outer mantle of the flame is repelled by the positive terminal of the battery. When the flame is close to this terminal, and is attracted by the negative terminal, the candle is close to the latter. When the negative terminal is in the form of a blunt point, a wing of the outer envelope of the flame is attracted to the surface of the blunt terminal and revolves around the point, sometimes touching the sharp point and then curving away from the point. This action seems to be due to the deposition of soot on the point.

I have spoken of the egg shape of the flame when it is apparently acted upon equally by the positive and negative terminals; and perhaps this remark requires further elucidation. When, for instance, the negative terminal is brought close to the edge of the luminous part of the flame, not touching it, and the positive terminal is moved toward the negative terminal, the flame shortens and spreads out laterally. When, however, the negative terminal touches the outer mantle of the flame, the effect of attraction to it becomes more marked. In these cases it would be difficult to distinguish the negative terminal from the positive by the actions on the flame. When, however, the terminals are approximately twice the striking distance of the battery, the flame of the candle is a ready indicator of the nature of the poles of the battery, being repelled by the positive pole and attracted by the negative.

When the positive terminal is a small sphere, the repulsive effect seems more marked than the flattening effect. When the terminals are slowly brought near each

[1] Neureneuf, Annales de Chemie et de Physique, Vol. II, p. 473, 1874; Holtz, Carl: Répert, Vol. XVII, p. 269, 1881; Pouillet, Ann. de Chemie et de Phys., Vol. XXXV, p. 490, 1827.

other, the singing of the non-luminous discharge is very distinct. Then a bright white, threadlike discharge occurs, which is immediately followed by a flaring yellow discharge, which, as I have said, can be drawn out 50 to 60 cm. with a difference of potential of 40,000 volts. These experiments illustrate forcibly the modern idea of ionization. The glow at the negative terminal shows that the entire air of the room between this terminal and the positive terminal of the battery participates in this ionization. It would probably be impossible by any method of insulation of the accumulator cells to insulate the positive pole of the battery so that this silent discharge would not manifest itself by this negative glow; for a large surface of any insulator, however perfect, in a limited form, becomes a conductor on account of its extended surface.

CHARGING CONDENSERS.

The form of condensers I have adopted is that of the so-called Franklin plate. These plates are 30 × 40 cm. The glass is 3 mm. thick for an accumulator of 10,000 cells, and 5 mm. for 20,000 cells. It is evident from the action of this large accumulator that the strength of current which the accumulator can deliver on a short circuit influences to a marked degree the insulating strength of the condenser which the accumulator charges.

The plates of the condensers are arranged in wooden trays with suitable switches, which enabled me to vary the number of plates. They were also arranged so that they could be charged in multiple and then discharged in series (Proceedings of the American Academy of Arts and Sciences, Vol. XXXIII, No. 24).

This form of condenser, namely the Franklin plate form, does not withstand the potential of the battery so well as the jar form of Leyden jar: a thickness of glass in jar form which will perfectly insulate the terminals of the 20,000 cells when charged to a difference of potential of 40,000 volts would break down when Franklin plates were used of the same thickness. I found that such plates could not be less than one-eighth of an inch, approximately 3 mm., in thickness to withstand constant use of the battery of 40,000 volts. The large storage battery illustrated in an interesting manner the time necessary to charge condensers to a definite potential. When the inner coating of a Leyden jar of about 10,000 electrostatic units is connected with one pole of the battery, and the other terminal rests upon a wooden table upon which the jar is placed, this jar will discharge through a small spark gap once in about ten seconds. When this latter terminal is connected directly with the outer coating of the jar, the rapidity of discharge increases to at least one hundred a second and appears continu-

ous. I was interested to ascertain whether the capacity at the terminals affected the breaking down effect in air and in oil. Without the external capacity, boiled linseed oil broke down between two small spheres one millimeter apart, under a difference of potential of 20,000 volts. A sheet of microscopic cover glass $\frac{1}{250}$ of an inch in thickness, however, was not perforated, and a sheet of mica $\frac{1}{1000}$ of an inch also withstood this difference of potential. When a capacity of 10,000 electrostatic units was connected to the terminals of the battery, no difference in the breaking down effect could be detected.

If, instead of the high resistance of the wooden table, a water resistance is intercalated between the poles of the battery and the Leyden jars, the same phenomenon is observed. The jars charge slowly to a sufficient potential, then discharge, and this discharge takes place with remarkable regularity; the smaller the resistance interposed, the more rapid the rate of discharge. The time of discharge can be regulated at pleasure by means of the water resistance, and the battery serves as a species of electrical clock.

The problem of a practical form of resistance early became an important one. I have used cadmium iodide resistances recommended by Hittorf. This form of resistance is useful for weak currents, but it heats under powerful currents. At one time it was thought that graphite resistances might be useful; accordingly a bank of graphite cylinders, made of compressed powdered graphite, were mounted on quartz columnar crystals. It was speedily found that these resistances had a large temperature coefficient, and moreover developed a large back electromotive force amounting to 500 or 800 volts when a difference of 20,000 volts was applied to the bank of resistances. I accordingly adopted a resistance of running water, which was very constant, having no temperature coefficient.

At the base of a large reservoir the water flowed out through a long horizontal tube. A wire introduced into this tube could be pushed in or out of it, and could thus modify the resistance in the circuit. A milliamperemeter introduced in the circuit with the water resistance gave perfectly steady readings.

The periodicity exhibited by the battery in charging condensers through large resistances is analogous to the periodicity shown by the battery in the recovery of the cells after each momentary short circuit. When the short circuits are repeated in regular succession, the striking distance of course diminishes, and also the distance to which the flaming discharge can be extended; finally, such a point is reached that the flaming discharge disappears, and the battery proceeds to discharge by means of bright white sparks resembling condenser discharges. This phenomenon is due to a

diffusion in the cells. Each period of exhaustion is followed by a period of recuperation; and one is strongly reminded of the action of the electrical eel, or the recuperation of human nervous force.

My experience with the mechanism necessary to charge and discharge storage cells leads me to remark that to the electrician the physiological theory of electrical currents in muscles and nerves is incomprehensible and not in touch with any phenomena exhibited by voltaic batteries or electrical machines; for a collection of muscles or nerves, which are apparently homogeneous in matter, or at least do not show marked differences in chemical constitution, can produce, it is said, an electric spark and shocks of considerable severity. If there exists in the separate muscles a source of electricity, in other words a difference of potential, what is the mechanism by means of which the muscles can be discharged in series? for the electromotive force of each muscle must be exceedingly low, and the high electromotive force of the electrical eel must be obtained by some mechanism which enables the animal to throw the effect of each muscle in series with the neighboring muscles. We cannot suppose that we have in these animals, which exhibit such marked electrical energy, a phenomenon like that shown in a thunder cloud. Meteorological observations lead us to conclude that the lightning discharge is not produced like the discharge from a great number of storage cells arranged in series, — that is, from one charged vesicle of water vapor to another, — but rather from the accumulation in series of such charges at some point on the surface of the cloud, the cloud thus acting like a charged condenser. We can thus suppose that the outer layer of vesicles of water are more heavily charged than those in the interior of the cloud. To suppose that there is any discharge in the heavens analogous to the discharge of a storage battery arranged in series, or, to go to physiology for a parallel, to suppose that there is a mechanism in the clouds similar to the arrangement of muscles or nerves in the electrical eel which permits by means of insulating sheaths the accumulation of charges, is to suppose something beyond the experience of the electrician. In short, the theory of animal electricity, in order to be accepted by the electrician, — a theory which supposes that each muscle is like a unit of a storage battery, and that these units are thrown into series in the case of the electrical fishes, — must show how, by an arrangement of nerves and circulation, such a coupling is possible.

The electrician too notices, even in recent books on the nervous system, an account of experiments to detect the induction of a stimulated nerve on a neighboring nerve. The account of such endeavors often immediately follows statements that the velocity of the nerve action is hardly one hundred feet per second. The

electrician knows that no inductive effect between one storage cell of much higher voltage than that of any nerve or muscle can be detected, even when the velocity of the electrical action in the inducing cell is many times that of the nerve action. To the electrician the supposed electrical condition of human muscles and nerves resembles that of a number of suburban towns, each with individual electrical plants not connected to any central station; and the physiologist who can show any ramifications which are analogous to those by means of which electrical energy is transmitted by inorganic machines would overcome much scepticism among physicists in regard to the real existence of electrical currents in human muscles and nerve.

There is, however, one analogy between the action of a storage cell and that of a nerve. This analogy can be found in the phenomenon of electrical diffusion. We recognize this diffusion in the ordinary voltaic cell, which is so universally used in ringing call bells and door bells. These cells discharge, so to speak, their electrical energy with a resultant fatigue, and, after a rest, are capable of exhibiting energy again. The electrical fish, it is said, recuperates after giving a shock. This recovery of a cell source of electricity is shown on a comparatively great scale by a large storage battery. This phenomenon is painfully apparent to the automobilist who drives an electric automobile; for it is an evidence of fatigue in his battery, and it gives an elusive hope of recovery. Have we not seen such an automobilist suddenly coming to a stop, and rest a moment, until by the phenomenon of diffusion in the battery the electromotive force rises sufficiently for him to proceed? An elusive hope, I have said, for another period of fatigue will soon set in, and the periods of necessary rest become longer and longer. In the rise and fall of electromotive force, due to diffusion, we have something very analogous to the recuperation and fatigue of nervous energy; and it is through the study of this phenomenon, I believe, that we shall gain some insight into the mysteries of what is called animal electricity.

The large storage battery of the Jefferson Physical Laboratory exhibits the periodic rise and fall of electrical energy in a manner most suggestive to one who thinks of the analogies between such a collection of units of electrical energy and the supposed collection of similar units in the electrical fish. When the battery is suitably connected to a reservoir like a Leyden jar, this reservoir rises to a definite electromotive force, and then discharges by means of a spark. The curve of rise and fall reminds one of the curves obtained by physiologists, denoting action and fatigue in the electrical conditions of muscles. The discharges of the battery can be so closely regulated that these discharges can be made as regular as the beating of the human heart. If

the novel of "Frankenstein" had been written in this century, the authoress would undoubtedly have equipped her automaton with a storage battery.

If a milliamperemeter is interposed between one terminal of the battery and one coating of the Leyden jar, the current rises to a definite value and remains stationary until the jar discharges. At the moment of discharge the reading of the amperemeter rises suddenly, and then falls to its steady value, — a value which depends upon the resistance interposed in the circuit. The rise in reading is evidently due to the diminished air resistance at the spark gap. The resistance of the spark is less than an ohm, or at least does not exceed two or three ohms. We can therefore form an idea of the magnitude of the resistance of the air in the case of the silent discharge, and indeed of the brush discharge.

The resistance of the silent discharge estimated in this way, — that is, by the fall in resistance when the spark passes between pointed terminals 2 cm. apart with a difference of potential of 20,000 volts, — is what is usually taken as the electric strength of the interposed layer of air. It depends upon the electric density, which, in turn, is a direct function of the voltage and amperage of the battery. The apparent resistance of the silent discharge thus depends upon the energy of ionization, and the latter is so much the greater, the greater the coated surface of the battery and the voltage and charge.

OSCILLATION OR PULSATION OF THE CELLS.

The discharge from a large number of storage cells, like that from a high-tension transformer giving a large amperage, is characterized by a sibilant flame which under a difference of potential of 40,000 volts can be drawn out to more than thirty inches. When a photograph of such a discharge is examined, it is seen to have a brilliant white spark as a nucleus. On account of the flaming nature of the envelope of this central discharge it is difficult to examine its character by means of a revolving mirror. By employing, however, two spark gaps, and maintaining fixed the terminals in the narrow gap, one can photograph the pulsations across this gap. Photographs obtained of the phenomena at this gap observed in a revolving mirror showed very regular pulsations or oscillations.

I have described elsewhere an apparatus for charging condensers in multiple and then discharging them in series.[1] Since writing this paper I have constructed a larger apparatus capable of giving sparks seven feet in length in air at atmospheric pressure. Up to one million and a half volts the length of the discharge is closely

[1] Proc. Am. Acad. of Arts and Sciences, Vol. XXXIII, No. 24, June, 1898.

proportional to the voltage; beyond this point leakage and electrostatic induction prevent accurate measurements. In order to study high voltage the apparatus should be lifted outside a building and placed high above the ground.

It seemed evident from observation of the phenomena that air at atmospheric pressure breaks down with great facility under high voltage combined with large amperage. The resistance of the electric spark varies greatly with the amount of current carried by the spark; and the non-concordant results obtained by different observers for this resistance can be explained by this fact. In one case I found that under a difference of potential of three million volts the spark passed through five centimeters of air in preference to a circuit through a solution of sulphate of copper of one thousand ohms resistance.

One is impressed in studying high voltage combined with large amperage that the study of electrical discharges by means of Holtz machines or other forms of glass inductors leads to limited conceptions of the amount of energy in lightning discharges. If Benjamin Franklin had worked with a high-tension storage battery, he probably never would have dared to try his celebrated kite experiment. Experience has shown that even five hundred volts combined with large current is sufficient to cause death.

The apparent diameter of the electric spark and its apparent direction are determined largely by physiological considerations.

To the eye, sparks of six or seven feet in length appear of at least a tenth of an inch in diameter. To obtain an idea of the size of the thread of luminosity, the discharge was passed through the finest needle hole in a plate of glass five feet square. This hole was made by plugging a much larger hole bored in the glass with paraffine and piercing the paraffine with a needle. When the spark terminals were opposite the hole, each one a foot and a half from it, the spark sought the hole and passed through it. A photograph shows an apparent breadth of spark much greater than the diameter of the hole. Possibly only a portion of the spark passed through the hole, for a surface ionization may have taken place over the surface of the glass.

In regard to the apparent direction of a lightning discharge I tried the following experiment. One observer changed the poles of the apparatus for discharging the condensers, while another, looking through an opening which concealed the spark terminals and only revealed the middle portion of the discharge, noted down his impressions of direction. On comparing the notes of the two experimenters, no agreement was found in regard to direction. This was also true when the discharge was made non-oscillatory.

Considerations of direction may arise from difference of luminosity and difference

of branching at the positive and negative terminals, for this difference exhibited by the two poles of discharge is very marked.

POWERFUL DISCHARGES OF ELECTRICITY AND A METHOD OF PHOTOGRAPHIC INTENSIFICATION OF THEIR IMAGES.

The discharges from a large number of condensers, charged in multiple and discharged in series, are probably more nearly identical with lightning discharges than any other forms of discharges within our experimental means; and the photographs of such discharges reveal details which do not appear in the discharges from Ruhmkorff coils or Tesla coils.

With a large portrait lens many of such details appear which are not shown by small lenses. These details, however, are difficult to reproduce. Indeed it often happens in scientific investigation that one obtains faint images which cannot be reproduced by any process of printing, and which do not give satisfactory results with ordinary processes of intensification or methods of repeated printing from quick plates to slow plates.

I have found the following method of obtaining strong contrasts in photography of electric sparks very useful in those cases where there is no general fog over the surface of the negative.

The negative is first intensified by iodide of mercury. The formula is given in most books on photography, and is as follows: Dissolve 14 grs. of bichloride of mercury in 700 c.c. of water and 42 grs. of iodide of potassium in 300 c.c. of water; pour the iodide solution into the mercury till the red precipitate formed is completely dissolved. For use, dilute with water and flow over the negative till the proper density is reached. When the negative is washed, it will turn yellow. I do not remove this yellow by hypo, for it is necessary to the complete success of the method of intensification.

When the negative is dry, it is placed in full sunlight in the morning, when the beams of the sun are nearly horizontal. By suitably inclining the negative one can obtain, in a portrait camera provided with a small stop, an image of the silver deposit, which appears white on a yellow ground. The resulting photograph is therefore also a negative. The faintest silver deposit is reproduced in marked contrast to the background, which has reflected a non-actinic yellow light, or at least a light less actinic than that reflected from the silver image.

I believe that this process of intensification is valuable in the large number of cases in which feeble images are obtained which do not lend themselves to the usual

process of printing by transmitted light. In many cases one can rest content with under exposures, feeling confident that good reproductions can be obtained by this method. Of course there is a certain amount of distortion on account of the angle of reflection, but this can be reduced to a minimum along certain lines which contain the part of the image which is the chief characteristic one seeks to show.

By suitably staining the plate with a yellow dye one can also place the negative in such a position in intense sunlight that the silver deposit, instead of reflecting a brighter image than the background or rest of the plate which contains no fog or image, reflects less light, and therefore appears black in sunlight. In this case one obtains in the camera a positive. This positive often reveals details which are not seen by transmitted light, and moreover gives them in strong contrast with the background or remainder of the plate.

Figure 8, Plate XXVI, shows two striking phenomena. The first is this: at every fork or zigzag along the path of the discharge there is a side discharge. These side discharges are directed toward the cathode. Moreover, each of these side discharges forks or bifurcates in the same manner; that is, they arise at the forks.

In the case of very long sparks, six feet or more, the bifurcations are generally directed to neighboring conducting masses, and are not directed to the cathode. In the case of lightning, masses of clouds at a low potential, not lying along the main direction of discharge, are indicated by these side forking discharges.

The second marked phenomenon is a brush discharge, exactly similar to the brush discharge at the anode before the disruptive spark occurs, at every fork or change of direction of this disruptive discharge.

Thus the peculiarities of the positive pole or anode are seen at every point of the disruptive discharge, especially when there is a choice between many cathodes. This choice can occur when the anode is a point and the cathode is an arc of a circle struck from the point of the anode as a centre, the arc being provided with several spurs or points. This bifurcation is seen in almost every lightning discharge, and it leads the observer to think that he can determine the direction of the lightning discharge, stretching out as it does like the fingers of a pointing hand.

Since the characteristics of the positive pole are so predominant in the disruptive discharge, one cannot help thinking that these characteristics show, so to speak, the superior momentum of the positive electron. In general the positive electron plays a minor rôle in electrical phenomena; but in the disruptive spark there is something characteristic of the positive pole — shall we call it the positive electron? — which completely overshadows the manifestation of the negative electron. We can consider that

in air with disruptive discharges at atmospheric pressure the Faraday column extends to the cathode, leaving no interval for a cathode space.

In air, however, at atmospheric pressure, as I have said, the negative glow at the cathode is far more noticeable than the positive glow when the terminals are far apart. For instance, the negative glow can be detected several hundred feet away from the positive terminal of the battery of 20,000 cells; while the positive glow only appears when the positive terminal is brought within two feet of the negative terminal. One marvels at the extent of invisible ionization extending from the cathode.

The characteristic brush discharge at the positive pole, a characteristic discharge which we see from Figure 8 is reproduced at every fork or bifurcation of the disruptive discharge, is shown in Figure 6. It is seen to consist of bifurcating discharges together with a flaming discharge. Turning to the negative pole (Figure 4) we find the brush discharges are straight, as if drawn in pencil with a ruler, except at their termini, where they end in a diffuse brush.

If the two discharge terminals are in the form of Neptune's tridents, the discharge often separates near the positive terminal, and the two portions appear at first to be undecided which of the points on the negative pole they will select. Finally they decide to unite. This phenomenon is evidently an evidence of the oscillatory nature of the discharge, for it shows that there are points of varying potential along the line of discharge.

Some years ago I showed that an explosion occurs whenever powerful sparks change their direction in zigzags, such as are evident in Figure 8. The spark passed between a plate of glass and a sheet of paraffined paper, and it was found that the paper was perforated at each forking of the discharge. This is shown in Figure 5, in which the spark negative is placed alongside of the negative of the perforations. Possibly these explosions occurring along an extended lightning discharge may be an important element in the phenomenon of the rolling of thunder, for the sound of such explosions would arrive at considerable intervals apart.

An interesting account of the explosive effect at each turning point of a lightning discharge has been given me by Mr. Harvey N. Davis, an instructor in the Jefferson Physical Laboratory, and I give it here, since it is an account by a skilled observer of both the above explosive effects and ball lightning.

"During the 27th of August, 1906, a large boarding-house on the side of Mount Moosilauke, in the town of Warren, N. H., was struck by lightning in an unusually sudden and severe thunder storm. The path of at least three independent discharges could be traced, but they must have been practically simultaneous, for those

who had been caught by the rain half a mile from the house, heard only one sharp report. One of the discharges struck the end of the ridgepole of the barn, and came down the wall to a very obvious ground; and two others landed halfway up the sloping roof of the nearest part of the house, one of them near, but not on a dormer window, and the other at some distance from any sort of a projection such as would ordinarily be expected to 'draw lightning.' In each place there was a spot about a foot across where the shingles had been forced outwards, as though by an explosion just under them, while inside there were two round holes four or five inches in diameter where the plaster had been blown into the room, leaving the laths completely bare. The first of these discharges travelled down the roof to the eaves, and jumped to the telephone wires, bursting out the shingles again as it left the roof. It happened that one of the young women of the house had just closed the dormer window, and was in the middle of the room with her head close to that part of the sloping ceiling where the second of the holes was found. It is possible that this was merely chance, or, on the other hand, her presence may have had some influence on the direction of the original discharge; at any rate, the discharge jumped to her right shoulder, and passed through or over the surface of her body to her left foot, then ran along the floor to the wall, leaving a mark such as might be made with a hot poker, and finally reached earth through the side of the house. The young woman was, of course, completely stunned, but was fortunate enough to escape serious injury. An interesting feature of this discharge was the regularity with which it seemed to explode every time it turned a corner. The explosions between the ceiling and the roof have already been mentioned; the next occurred when the discharge reached the woman's foot. Her shoe and stocking were blown completely off, so that only the left half of the upper of the shoe remained attached to the sole. From her foot it ran along the floor to a tin pail, which was standing on a piece of linoleum, and here it exploded again, overturning the pail, and demolishing the linoleum, some of which was found inside a water pitcher on a stand near by, while one or two shreds reached an adjacent windowpane with force enough to stick between the glass and the sash. Finally, the point where the lightning reached the wall and started down between the sheathing and the plaster was very plainly marked on the outside of the house, a couple of clapboards being forced out several inches. In the room below, the plaster was loosened from the laths all the way down, probably by the pressure of the heated air, but the appearance was quite different from that of the ceiling in the room above. Fortunately nothing took fire.

"At the time of the discharge the guests were in the dining-room at the other side

of the house, and several of those who turned most quickly saw slow moving ball discharges just outside the window. One of those with whom I talked, a trained scientist, was sitting with his back partly turned, and saw only one ball of fire, 'like a glowing coal'; but others said that it had been preceded by one rather larger, perhaps as large as a baseball. When he first saw the second ball, it was three or four feet from the ground, and was falling obliquely, as though it had rolled off the roof of a low ell near by, and its velocity was only a few feet per second, — certainly not enough to leave a streak on his retina, as he noticed at the time. We searched that night, and again carefully the next day, for traces of these discharges in the ground, but could find none. Whether they were independent discharges from the main cloud, or were secondary effect, due to the electrification of the wet roof, I do not know. At any rate, they were not immediately connected with either of the three main discharges, for two of these went to obvious grounds, as has been indicated; and the telephone wires, which carried off the third, were nowhere near the part of the house where these balls were seen."

In long discharges of lightning these explosions, directed at varied angles, could give rise to sound waves, which, starting practically at the same instant, nevertheless, by different angles and degrees of reflection, could arrive at the ear of the listener at considerable intervals, and produce the rolling of thunder.

What, then, are the conclusions that can be drawn from the foregoing manifestations of electric discharges which can be produced by a large number of storage cells? The first fact which impresses one is the importance of the consideration of amperage as well as electromotive force. Throughout scientific literature, and in popular conception, electromotive force has received the chief consideration in discussing the phenomena of lightning. Experiments in laboratories have been conducted with electrical machines which are generally incapable of affording much current. Franklin's experiment with the aid of a kite illustrates an underestimate of the current in a lightning discharge. Even to-day no one would think of repeating Franklin's celebrated experiment, largely from a dread of voltage, but with little conception of the possibility of danger from small voltage and large current. We are beginning to realize, however, that 500 volts, accompanied by a current of from 10 to 20 amperes, is sufficient to destroy human life. One compartment of the storage battery which I have described in this memoir, — a compartment affording something over 800 volts, — short-circuited through the body of the janitor of the laboratory, was sufficient to knock him senseless.

The most powerful electric discharge which we can produce by modern appliances

is a faint shadow of lightning, — so faint that it fails to reproduce in most essential respects the phenomena in the heavens. I have never been able, by the use of resonant tubes or other arrangements, to cause reverberations to reproduce in the slightest degree, even with sparks six feet in length, the rolling of thunder. The energy of an ordinary lightning discharge must be enormous.

The forms of lightning discharges are very varied, and when one asks whether lightning is oscillatory, one should specify the kind of discharge.

SPECTRUM ANALYSIS WITH CURRENTS OF HIGH ELECTROMOTIVE FORCE AND STRONG CURRENTS.

For several years I have been endeavoring to obtain new series of hydrogen lines which might presumably manifest themselves at very high temperatures. In the progress of this work I have obtained a number of interesting facts, but I have failed to find a new series of hydrogen lines; possibly the reactions both in glass and quartz vessels mask the series. It seems impossible to experiment at a higher temperature than I have obtained, certainly if one employs such vessels as I have mentioned.

The advantages in using a storage battery for experiments in spectrum analysis are well recognized. These advantages are especially seen in the employment of condenser discharges. When the condensers are charged through a large liquid resistance, they charge to the same potential each time, and then discharge, without the intervention of a discharger, through the Geissler tube. The number of discharges can be closely regulated by the amount of liquid resistance which connects the poles of the condensers to the battery. The regularity of such discharges through the Geissler tubes is remarkable. In popular language one can call the arrangement an electric clock, for the discharges follow each other at regular intervals. In this way one avoids the spark at a discharger and is sure of always obtaining the same difference of potential at the ends of the Geissler tube.

The highest temperature to which one can submit a gas is presumably that of the electric discharge from a condenser; opinions differ in regard to the degree of heat which one can obtain by such a discharge. The limit I have reached is the volatilization of silica, — perhaps 1800 degrees. At this temperature the spectrum shown by all gases in narrow capillary tubes consists of a continuous spectrum crossed by broad bands due to silica or to an oxide of silica; the gaseous spectra are completely masked. This masking seems to be due to the greater conductibility of the volatilization products from the walls of the tubes and from the metallic terminals. It seems to me

that this variation in conductibility is sufficient to account for the phenomena of masking without recourse to a theory of electrons which provides for suitable damping of electrical oscillations. The electron theory may be an ultimate explanation, however, of electrical conduction.

I speedily found that the limit of resistance of glass tubes enclosing rarefied gases was low, and that it was impossible to utilize to its full extent the amount of energy which was at my command. Geissler tubes filled with oxygen, hydrogen, and nitrogen all gave the same spectrum when sufficiently strong discharges were passed through the tubes. This is also the case with quartz tubes. It seems to be impossible to so exhaust tubes and cleanse them to such a degree that high electromotive force and strong heating effect will not drive off occluded gases or closely adhering layers of gases. It is not impossible, moreover, even if the surface layer of adhering gas is removed, that it is replaced by gases coming from the interior of the glass. It is well known that glass holds water vapor in its mass, and quartz permits the passage of hydrogen when the quartz is incandescent.

On account of the difficulty of leading platinum wires, air tight, into quartz vessels, the ends of the quartz tubes which had been blown out into bulbs were carefully ground and were luted to glass bulbs by means of silicate of soda. The electrodes were led into the quartz bulbs as far as possible to avoid the volatilization of the silicate of soda; or at least to prevent the result of this volatilization from reaching the capillary. One of the most striking facts which the investigator in spectrum analysis meets in the study of electric discharges through exhausted tubes is the difficulty of getting rid of impurities which arise from the methods of exhaustion. The mercury used in the process of exhaustion provides mercury vapor, — which, however, is the least source of trouble, for it can be frozen out by liquid air. A more serious trouble arises from the lubrication of the valves of the pump. This lubrication is a large source of carbon monoxide, traces of which are rarely absent if strong discharges are employed. Moreover, the substances used by chemists to dry gases are an unfailing source of impurities, which are revealed by the astonishing delicacy of spectrum analysis.

The student who endeavors to obtain a spectrum of hydrogen with strong discharges is apt to become sceptical of conclusions based upon this delicate method of analysis, for he must confine his study to comparatively weak excitation of the rarefied hydrogen. The moment he employs a powerful discharge all trace of hydrogen disappears, and he must conclude that there is some phenomenon of occlusion of chemical combination or masking. What astonishes one most, perhaps, is the

occurrence of what is ordinarily called the four-line spectrum of hydrogen when an exhausted tube is filled with water vapor. The readiness with which this four-line spectrum can be obtained in water vapor, and the comparative difficulty of obtaining it in dry rarefied hydrogen with powerful discharges, leads to much reflection. Is it not possible that the common occurrence of this spectrum of hydrogen among the stars, and especially in the atmosphere of the sun, is an evidence of the prevalence of water vapor and consequently of oxygen?

The following experiment is of interest in this connection. The object of the experiment was to determine whether the mass law of physical chemistry applies to a mixture of hydrogen and oxygen.

An end-on Geissler tube T was connected to a mercury pump which was provided with a McCleod gauge, and also with a tube of ignition tubing in which oxygen could be generated by heating the enclosed peroxide. Close to the Geissler tube was a bulb filled with distilled water. By opening a valve the Geissler tube could be filled with steam from the heated bulb, or with water vapor at a lower temperature than steam. Another end-on tube filled with hydrogen at a definite pressure was separated from the pump and served as a comparison tube. The same current from the storage battery was led through both the tube connected to the pump and this comparison tube. A prism provided with silvered mirrors on its sides received the light from the two end-on tubes and a straight vision spectroscope gave a spectrum line from each tube side by side. I selected the red line of hydrogen for comparison, and moved the end-on tube which was not connected to the pump to and fro until the lines seen in the spectroscope appeared to be of equal brilliancy. This method of observation seemed to be sufficiently exac tfor the purpose of the experiment. At one time a spectrophotometer consisting of the well-known arrangement of two nicol prisms in connection with a straight vision spectroscope, was tried; but it was not found necessary to proceed to the degree of refinement offered by such an instrument.

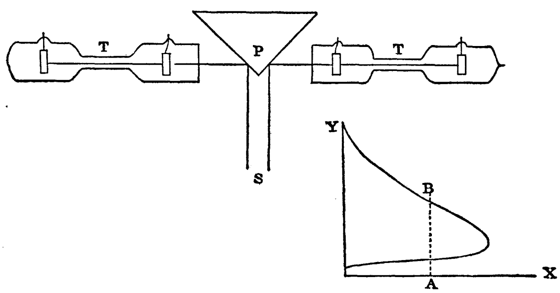

FIGURE *B*.

The tube containing water vapor was exhausted to a certain pressure, and the separated tube was adjusted until the brilliancy of the red lines in the two tubes appeared to be equal under the same current; then varying amounts of oxygen were admitted to the tube connected to the pump, and the brilliancy again compared after

the tube in each case had been exhausted to the same degree. It was speedily seen that a great excess of oxygen did not result in dimming or decreasing the brilliancy of the red line of hydrogen. On the contrary, up to a certain point the addition of an excess of oxygen increased the brilliancy of the hydrogen line. The mass law of physical chemistry, therefore, does not seem to apply in the spectrum analysis of water vapor and oxygen. If one plots the intensity of the hydrogen red line as an abscissa and the pressure of the exhausted tube as an ordinate, one can represent the changes in intensity of the line by a curve. The intensity increases as the exhaustion proceeds, until, the current being kept constant, when a certain pressure is reached the brilliancy of the red line in the tube connected to the pump begins to diminish. The curve representing the run of intensity has a point of inflexion and returns to the axis of Y; thus between the origin and this point of inflexion there are two values of pressure giving the same intensity. The hydrogen line diminishes in intensity as the amount of water vapor diminishes, the strength of exciting current remaining constant.

This experiment illustrates the fact that oxygen can be present with an excess of water vapor and yet does not manifest itself spectroscopically. One should not, therefore, conclude from the absence of oxygen lines in the solar protuberances and in the hydrogen types of stars that oxygen is not present. It is maintained by some that hydrogen in such a mixture and water vapor and oxygen carries the current, and that the oxygen, on account of its resistance, does not participate in this electrical action. However this may be, we still cannot conclude from the absence of oxygen lines in the spectrum of the solar protuberance that oxygen is not present.

REVERSALS OF METALLIC LINES.

The discharge of powerful condenser sparks between metallic terminals 1 cm. apart, in glass or quartz tubes of 1.2 mm. diameter, filled with rarefied gases, affords interesting spectra. In general, the strongest lines of the metals employed as terminals are reversed. These reversals (dark lines on the positives) coincide in position with that of the same lines in air, while the general broadening of the line is toward the red. This fact is clearly seen in the spectrum of the line of silicon wave length 2881 (Figure 9, Plate XXVII). Thus we have the effect noticed in the spectrum of certain variable stars, — a line dark on one side and bright on the other. A slight reversal, not sharply evident, might lead one to conclude that there had been a shift on the whole of the line in question toward the red. A changing thickness, or

density of vapor, together with a Doppler effect, might be important elements in producing small displacements.

It is only when the metallic terminals are close together — three to four centimeters or less — that these phenomena are observed. Indeed, even with sparks of six feet in length in air, thus indicating a very high electromotive force, no spectroscopic evidence of the metals of the spark terminals can be obtained at a distance of three inches from such terminals. The particles of the metals are apparently too heavy to be projected to any considerable distance, and the spectrum obtained is that of heated air.

In the study of displacements seen in comparison of spark and arc spectra, the phenomenon I have observed may have importance; for, by changes in position of the metallic electrodes and change in pressure of the rarefied gas, one can vary the conditions over a wider range than when the study is made in atmospheric air at atmospheric pressure. It is evident that when the terminals are within 1 cm. apart, powerful condenser discharges approach the condition of the voltaic arc. The pressure produced by powerful condenser discharges in capillary tubes is perhaps an element in producing the broadening of the lines toward the red.

In Professor J. J. Thomson's "Conduction of Electricity through Gases," 1906, p. 516, the subject of pressure in the spark is considered from the point of view of the kinetic energy given to the ions, and the author calculates that this energy of a spark 1 cm. long in air at atmospheric pressure, from a condenser of 1000 cm. capacity charged to 30,000 volts, if distributed throughout 1 c.c. of gas, would increase the pressure by 6.6 atmospheres. When confined to the very much smaller volume traversed by the spark, the pressure would rise to enormous values. To take $\frac{1}{100}$ of 1 c.c. as the volume of gas traversed by the gas, which would be a large overestimate, the initial pressure along the path of the spark would be 660 atmospheres.

When terminals of different metals are employed in capillary tubes of glass or quartz, and are separated four or five millimeters, complicated phenomena result from powerful condenser discharges through the rarefied gases contained in these tubes.

All specimens of glass which I have tried — soft German glass, lead glass, Borsilicon glass, or Jena glass — give broad bands due to silica; lead glass gives, in addition, lead lines. Jena glass gives a very strong line of boron at wave-length, 3451.49. These lines and bands are obscured by a continuous spectrum.

The narrow capillaries with metallic terminals which I have used may be called electric furnaces, in which there is no permanent product or permanent decomposition; moreover, the spectra which we observe do not reveal all that the capillaries

contain. Hydrogen may be present, but it is concealed. Oxygen shows its presence only by probable oxides; the constituents of rarefied air are undoubtedly always there. The conditions which prevail in the case of discharges in such narrow capillaries seem to be analogous to those in the case of discharges under liquids. In this latter case we also have reversals of metallic lines; and, moreover, certain characteristic lines of metals are wanting. See "Spectra from the Wehnelt Interrupter," Harry W. Morse, Proceedings American Academy of Sciences, May, 1904.

These results make one doubtful in regard to the entire subject of spark spectra which are observed between metallic terminals in ordinary air; and we are forced to ask, what influence does the environment have upon the character of these spectra, — to what must we attribute the absence of oxygen lines? And even if we take spark spectra between metallic terminals in an atmosphere of hydrogen or nitrogen, we are not sure that the results are not modified by the gases which are occluded in the metallic terminals.

Are we sure that, even in electrodeless tubes, helium is a product of disintegration of radium, a transmutation, so to speak, and is not a result of the electrical stimulus in the environment of glass or quartz, — a stimulus which may bring to light the helium which has refused to manifest itself by chemical analysis?

In general it may be said that the conductibility of the volatilization products, either from the walls of the tubes or from the metallic terminals, determine the occurrence of the spectral lines or bands. The spectrum, for instance, of silica completely masks the spectrum of the iron terminals when the latter are placed not more than five millimeters apart. When the terminals are of different metals, the spectrum of the more volatilizable metal predominates; or, more strictly, the spectrum of the better conducting vapor.

Another striking fact brought to light by such discharges in capillaries is the reversal of many of the spectral lines on broad bands. The broadening of the lines of the metals is generally toward the red end of the spectrum. The quantity of the discharge appears to be the important factor in determining the character of the spectra; electromotive force, *per se*, does not give new lines which can be detected by photography. The effect of high electromotive force begins to be evident at high exhaustions, and then only in producing cathode and X rays.

This latter fact can be well shown by a Tesla coil, actuated by a Cooper-Hewitt mercury interrupter, such as was employed by Dr. G. W. Pierce, Proc. Amer. Acad., 1904. With a suitable step-up transformer, in connection with such an interrupter, I have studied the spectrum of hydrogen, and have not obtained a spectrum which

differed from the one obtained by the same amount of energy with lower voltage. The high voltage ranged from 100,000 volts to 3,000,000.

The broadening of metallic lines seems to indicate an oxidization. One can conceive of a loading of the metallic molecule by various degrees of oxidization which leads to a broadening toward the red end of the spectrum; or, in other words, to longer wave-lengths, and an unloading due to dissociation, which leaves the molecule free to emit shorter wave-lengths. That an oxidization results from a discharge of electricity in glass or quartz tubes, filled even with apparently pure hydrogen, seems to me to be evident from my experiments. The unavoidable presence of water-vapor in glass and, I may add, in quartz tubes, lends color to the oxidization theory; this vapor is dissociated by the electric current, the oxygen set free combines with the molecules of the metals, or with the molecules of silica and its metallic impurities.

The following experiment illustrates this oxidization. A Geissler tube (Figure *C*), with an internal diameter of one inch, was provided with an inner capillary, one end of which was blown to the walls of the larger tube; the other end was free inside this larger tube. An electric discharge passed between two ring electrodes A and B, which were placed in the larger tube. The discharge therefore started, so to speak, in the larger tube, passed through the narrow channel of the capillary, and emerged to the cathode. The tube was filled with pure hydrogen, dried by phosphoric pentoxide. Under the effect of powerful condenser discharges, the four-line spectrum was much enfeebled in the capillary; the red color, characteristic of condenser discharges in hydrogen, gave place to a brilliant white light, and when the capillary was viewed end on, a continuous spectrum was seen. When, however, the discharge issued from the capillary, a brilliant aureole was seen around the end of the capillary; this aureole gave a much enhanced four-line spectrum. The temperature inside the capillary was sufficient to volatilize the walls of the capillary, and therefore was competent to decompose the water-vapor into oxygen and hydrogen. Just outside the capillary the temperature fell to the point of recombination of these gases to water-vapor, and the enhancing of the red hydrogen line which is always observed in water-vapor.

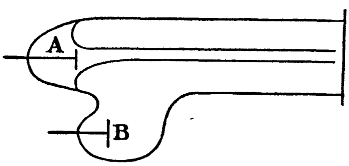

FIGURE *C*.

In another experiment the Geissler tube (G, Figure *D*) was placed between two manometer gauges, and was exhausted to such a degree that the electric discharge failed to pass. One end of the Geissler tube, that nearest to the pump, was shut off

by means of a stop-cock B; and dry oxygen was admitted to the pump until the manometer gauge connected with the pump indicated two centimeters pressure. The stop-cock was then opened so as to admit the gas to the Geissler tube. The corresponding manometer gauge at the opposite end of the Geissler failed to register the requisite equalization of pressure, there having arisen an oxidization of the mercury meniscus by means of which the capillary constant between it and the glass had been changed. This holding of the mercury meniscus was large and had to be overcome by vigorous tapping of the tube. An analogous effect was obtained when the Geissler tube was filled with rarefied air, and also when it was filled with nitrogen. When, however, it was filled with dry hydrogen, the holding effect was comparatively inappreciable. The oxygen produced by the dissociative effect of the electric discharge combined with the hydrogen and no longer oxidized the surface of the mercury. In this connection it may be observed that the mercury meniscus in the Lippman electrometer is affected principally when it is made the positive pole, and therefore oxygen is liberated.

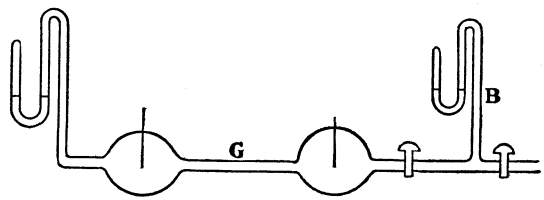

FIGURE *D*.

Perhaps the most striking experiment in this connection can be made with the steady current from a large storage battery. When Geissler tubes, preferably of half a centimeter internal diameter, are provided with copper terminals, and are filled with dry hydrogen at pressures of one millimeter to one-tenth of a millimeter, a steady diminution in the pressure of the gas results from the application of the discharge; the light of the spectrum grows dimmer and dimmer, then the cathode rays appear, finally the X rays, and then no discharge can be forced through the tube until a much higher electromotive force is employed, or heat is applied to the tube. This heat evidently drives off water-vapor from the walls of the tube together with air; a fresh application of the steady current again diminishes the pressure in the tube to an apparent vacuum. Thus one can exhaust, so to speak, a Geissler tube by employing a steady current of electricity to dissociate the ever present water-vapor. With copper electrodes, the oxidization produced by this dissociation is more evident than with other metals; although I have observed it with magnesium terminals, with iron terminals, and with other metals.

These experiments lead me to believe that, just as in chemical reactions, a certain amount of water-vapor or humidity is essential to conduction in gases whether brought about by what is called chemical affinity or electrolytic action.

I have dwelt upon the broadening of the lines of metals in capillary tubes. This phenomenon is also observed with hydrogen lines, and was first noticed by Liveing and Dewar, Chem. News, XLVII, p. 122, 1883. These authors attributed the broadening to compression of the gas in the narrow capillary under the effect of a powerful condenser discharge. Their method of experiment was as follows: The tube was exhausted only to perhaps five or six centimeters pressure, so that a white discharge of a spark nature passed through the capillary and then spread out to electrodes placed in the large ends of the tube. When the tube was viewed end-on, a continuous spectrum was seen in the capillary; moreover, this continuous spectrum was crossed by a dark line which resulted from the absorption of heat in the colder layers of gas in the larger portions of the tube.

The broadening of the spectra of the vapors of metals which I have observed in capillary tubes has thus its analogy in the case of gaseous spectra.

Having obtained reversals of the spectra of metallic vapors under new conditions, I was naturally interested in the experiment of Liveing and Dewar, especially since a controversy had arisen between M. Cantor and E. Pringsheim in regard to the possibility of the reversal of gaseous lines in Geissler tubes. M. Cantor[1] concluded from his experiments that such reversals do not occur in the phenomena of luminescence, such as one obtains by the discharges of electricity in Geissler tubes. Pringsheim objected to these conclusions on the ground that Cantor did not observe a sufficiently narrow portion of the spectrum of the gas and did not use sufficient dispersion. Pringsheim[2] quotes the result of Liveing and Dewar in support of his position.

In repeating Liveing and Dewar's experiment, it occurred to me that objection might be brought against it on the ground that it was a spark discharge and not a clearly marked glow or luminescent discharge such as Cantor evidently had in mind. I therefore placed a second spark gap (S, Figure *E*) just outside the inner capillary of the large Geissler tube provided with an inner capillary, as I have previously described in speaking of the temperature inside a capillary, and in the space just outside. The discharge passed first through the capillary, and then by means of an outside connection through the second spark gap; thus the light from the capillary passed through the light from the second spark gap. In both cases

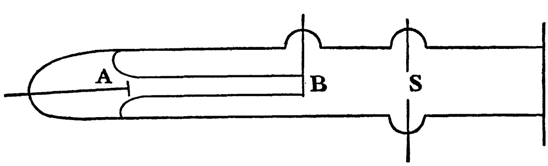

FIGURE *E*

[1] Ann. der Phys., n. 3, 1900, p. 462.

[2] Ann. der Phys., n. 5, 1900.

the light was a glow or luminescence and not a white spark discharge, the pressure in the tube being from one to two centimeters.

A Rowland grating was employed, and an eyepiece was fixed on the C line of hydrogen. The second spark gap gave a fine bright line of the apparent length of the slit, the capillary a continuous spectrum, and where the fine bright line crossed this continuous spectrum, it was reversed.

Kirchhoff's law of radiation thus applies to the radiation in Geissler tubes, and Pringsheim's contention is justified. If the solar corona is an electrical phenomenon of the nature of luminescence it can exhibit either bright lines or dark lines according as it is hotter or colder than the background.

In this study of the upper limit of temperature which one can reach by electric discharges through rarefied gases, we perceive that spectrum analysis is one of the most difficult analyses which modern science has revealed. There are a few broad facts, such as Doppler's principle and the reversal of spectral lines according to Kirchhoff's law; on the other hand there is ionization, dissociation, adsorption, and absorption, all modified by the glass or quartz vessels which must be employed.

M. Cantor calls attention to the fact that Hittorf failed also to observe reversals of spectral lines in the case of electric discharges in Geissler tubes. Hittorf speaks of a first series of hydrogen lines which are seen with feeble discharges. This feeble spectrum with its bands seems to be a peculiarly luminescent effect in which any translatory or colliding effect of the molecules is a minimum. The new theories in regard to the composite nature of the atom seem to demand an extension of our views in regard to the nature of the light emitted by atoms and their aggregates under the stimulus of an electric discharge. The phosphorescent and fluorescent light of a gas under this stimulus may arise from the mechanism of the atom, and therefore may not give sensible heat. The combination of atoms into molecules, and their dissociation and formation of new combinations, may give the spectra we usually observe under the effect of fairly strong electric discharges, and provide the sensible heat which can be measured by the bolometer or the thermal junction.

Spectrum analysis of the future thus becomes more and more difficult of application, and one of its most important fields is in the study of phosphorescent and fluorescent light emitted by gases. We seem to be on the point of regarding the light and heat of the sun more from the electrical standpoint. And the study of discharges of electricity in rarefied gases assumes a great importance.

My attention was first directed to the phenomenon of reversals in Geissler tubes filled with rarefied gases by the reversal of two lines apparently closely coinciding with

the H and K lines of the solar spectrum. It did not seem possible that these lines could be due to calcium, for I obtained them in quartz tubes.

I have, however, made a more extended examination of the possible origin of these lines from the calcium contained in glass, using quartz tubes, and although I occasionally obtained these lines with quartz tubes, I am now persuaded that these lines are due to calcium; for using the utmost care in luting pure silver terminals into quartz tubes, the luting being at a great distance from the point of discharge, I found difficulty in obtaining the lines, and in the majority both lines did not appear. There was, however, in the case of quartz tubes one line coincident with one of the calcium lines and nearly coincident with the H line of the solar spectrum. It seems evident that in the immediate region of the H and K lines, perhaps superimposed upon them, are gaseous lines. At one time I thought that oxygen might contribute lines to this region, but I am less sure of this from subsequent investigations.

It is evident, I think, that the characteristic spectrum shown in Figure 9, Plate XXVII, is due to silica; for it appears in quartz tubes as well as in glass tubes with very powerful discharges in rarefied oxygen, hydrogen, and nitrogen.

The region, however, in the immediate neighborhood, or included in the broad region of the H and K lines, is a composite one, and must be investigated by a spectroscope of greater dispersion than that I have employed. The one I have used gives a space of approximately 4 mm. between these lines.

Figure 10 shows the change in the spectrum of rarefied air in quartz tubes with increasing strength of discharge; the gaseous lines diminish in number, and the final spectrum is characterized principally by two very broad bands.

The spectra of the discharges in the Geissler tubes were produced by discharges from a large condenser and varied in number from one discharge to six discharges. The discharge number one is close to the solar spectrum (Figure 10, Plate XXVII). The spectrum resulting from six discharges is furthest from the solar spectrum. It is evident from the study of these discharges that certain lines appear with comparatively weak discharges which disappear with stronger discharges.

Figure 9 shows the flashing of a silicon line, 2881, toward the red end of the spectrum. This flaring toward the red can be seen in the case of most strong metallic lines obtained in capillary tubes filled with rarefied air.

RESULTS.

1. Hydrogen lines do not increase in number with the most powerful electric discharges which glass or quartz can withstand.

I have not been able to produce the new series of hydrogen lines discovered by Professor E. C. Pickering in the spectrum of certain stars.

2. The limit of strength of current and electromotive force that one can employ in the study of gaseous spectra of rarefied gases is far below the safety limit of the glass or quartz tube which is employed, for the containing vessel contributes many impurities which come into strong evidence with powerful discharges; moreover, the resulting continuous spectrum completely masks the line spectrum.

3. It seems probable that many of the lines in gaseous spectra are composite lines, especially those which are seen with condenser discharges. The so-called four-line spectrum of hydrogen is enhanced by the presence of water-vapor.

4. A characteristic spectrum common to rarefied oxygen, hydrogen, and nitrogen, is obtained in glass tubes and quartz tubes when the limit of safety of the tubes is approached. (Fig. 11, Plate XXVII.)

5. The red line of hydrogen, 6562.10, can be reversed in a tube filled with rarefied hydrogen.

6. In general it is difficult to determine whether one has succeeded in reversing gaseous lines in the case of powerful discharges through rarefied gases on account of the continuous spectrum which occurs.

7. Metallic spectra obtained in capillary tubes filled with rarefied air are characterized by a reversal of most of the strong lines, with a pronounced broadening or flare toward the red end of the spectrum. This phenomenon occurs with powerful condenser discharges.

8. Powerful electric discharges in air resulting from the discharge of many condensers in series exhibit at each fork or angle of the discharge brush discharges characteristic of the positive pole; and also an explosive effect.

9. Beyond 3,000,000 volts the leakage and inductive effects inside a building prevent even approximate measurements of relation of length of discharge to voltage.

10. The new construction of the large storage battery described in this memoir will, I believe, greatly add to its life and usefulness; for the battery can be short-circuited without fear of injury. The lead plates in the first form of battery were renewed once in twelve years. A battery of 20,000 cells forms a unique installation for a physical laboratory, and contains the promise of great usefulness, especially in cases where uniform and steady electric fields are necessary.

JEFFERSON PHYSICAL LABORATORY,
HARVARD UNIVERSITY.

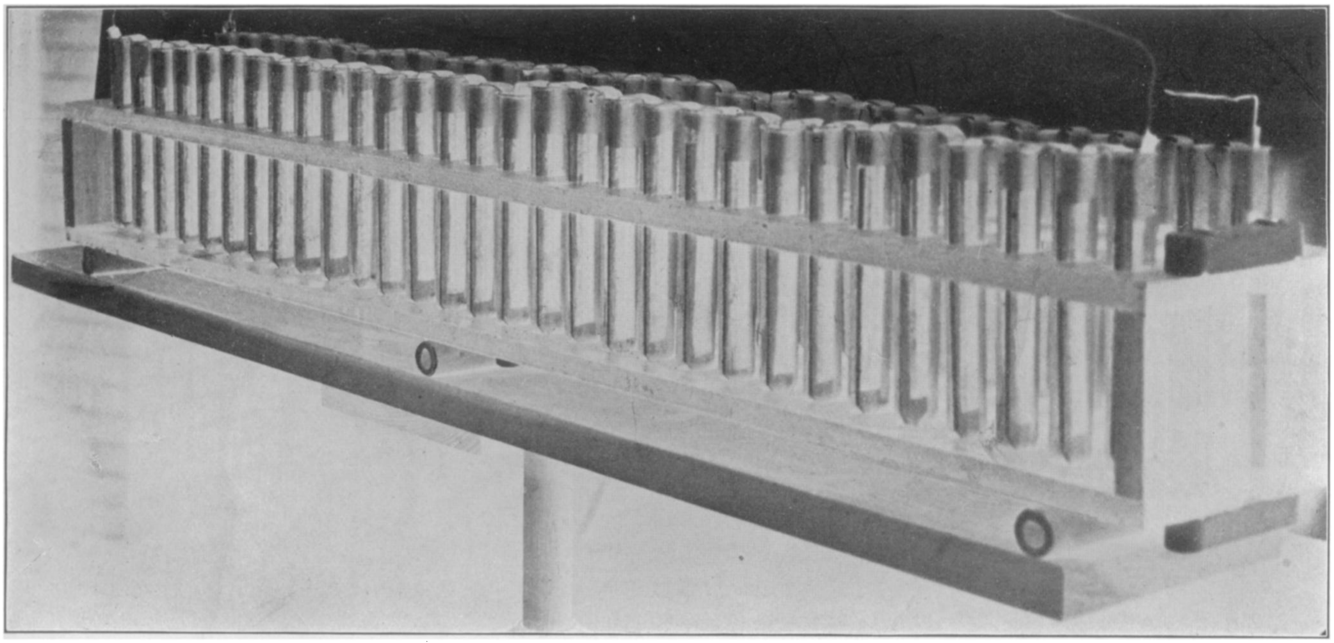

FIG. 1

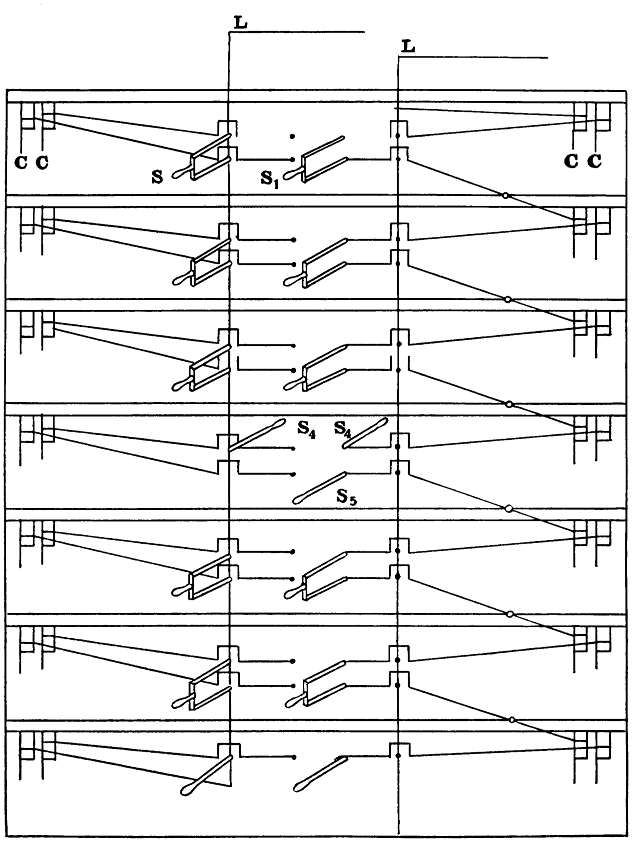

FIG. 2

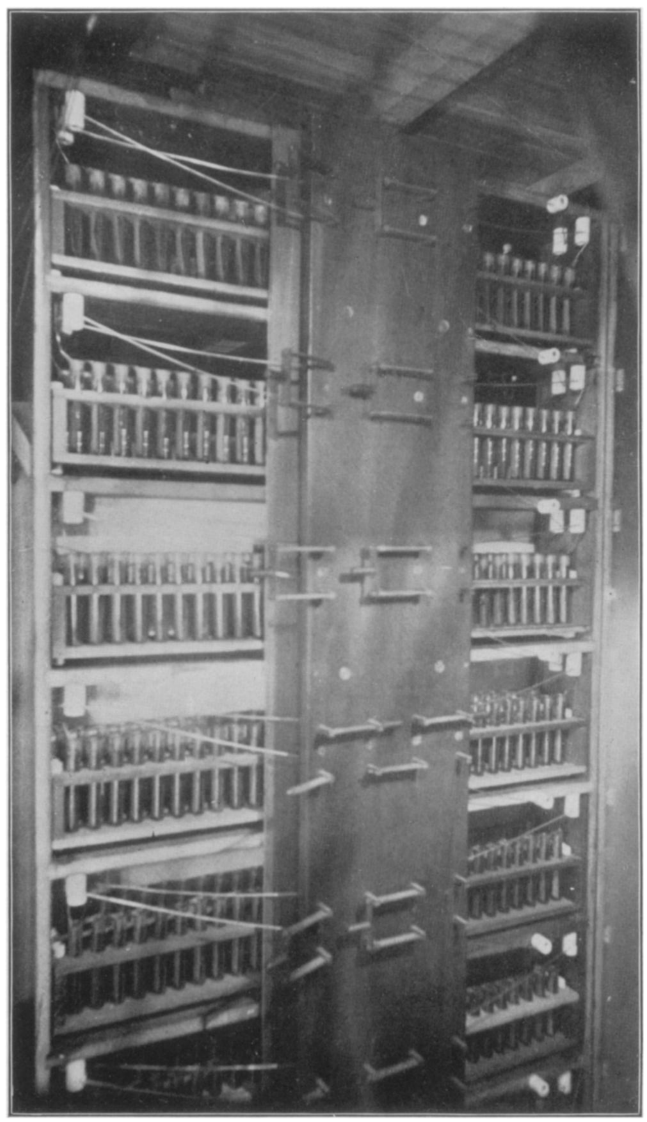

FIG. 3

TROWBRIDGE.—HIGH ELECTROMOTIVE FORCE

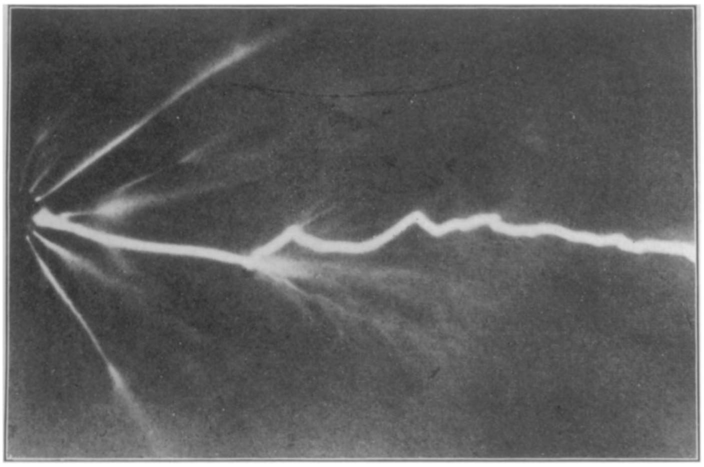

FIG. 4

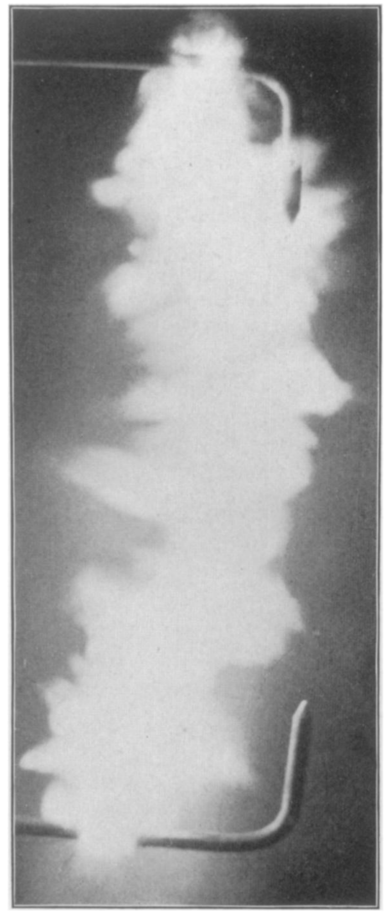

FIG. 7

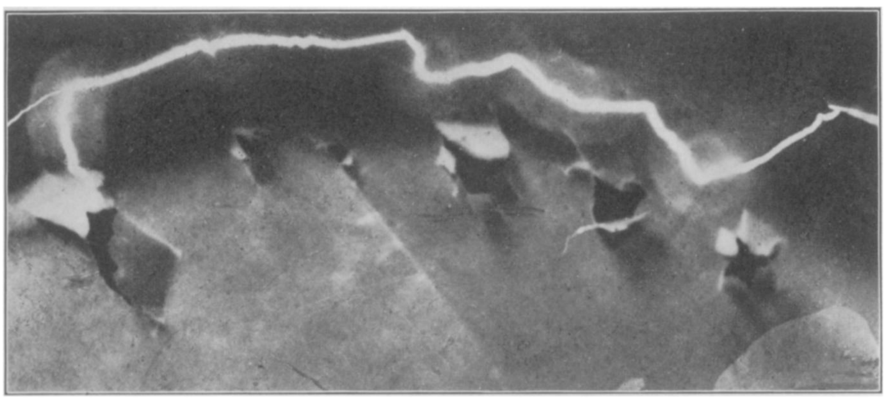

FIG. 5

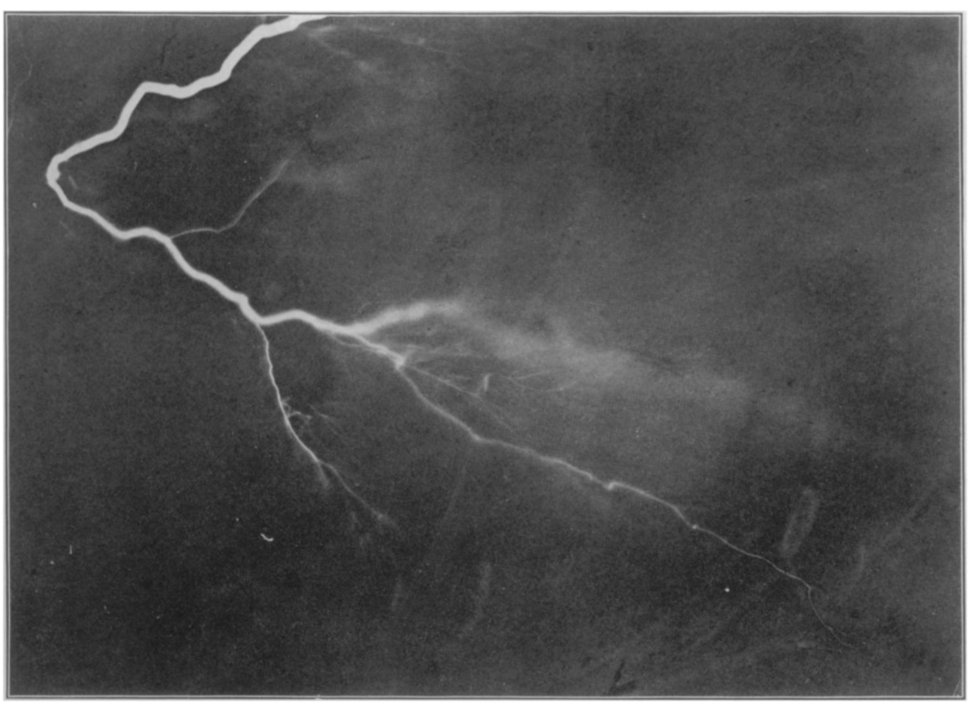

FIG. 6

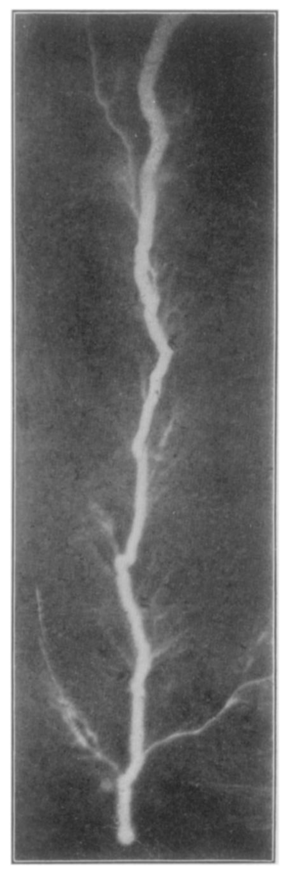

FIG. 8

TROWBRIDGE.—HIGH ELECTROMOTIVE FORCE

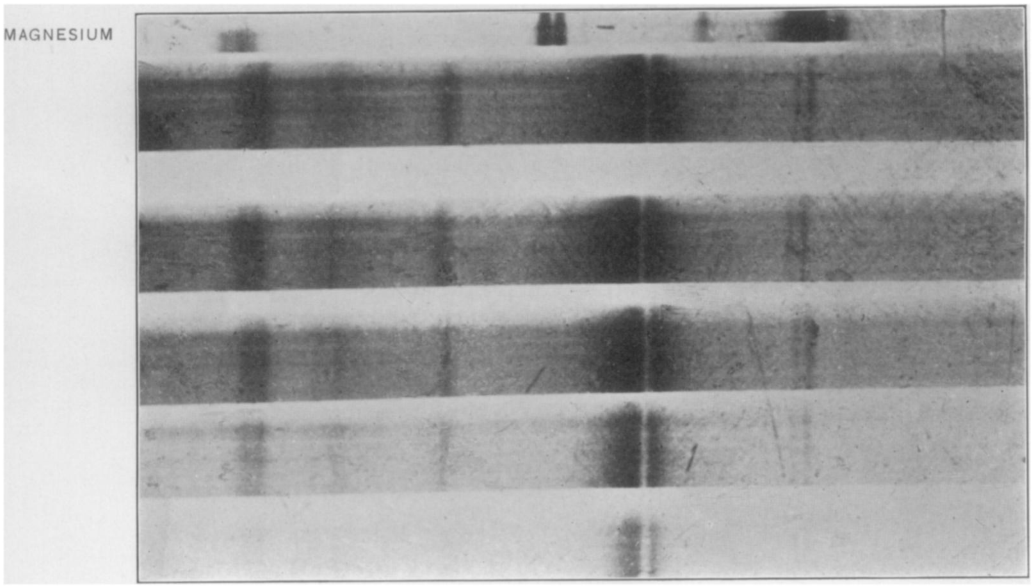

FIG. 9 (NEGATIVE)

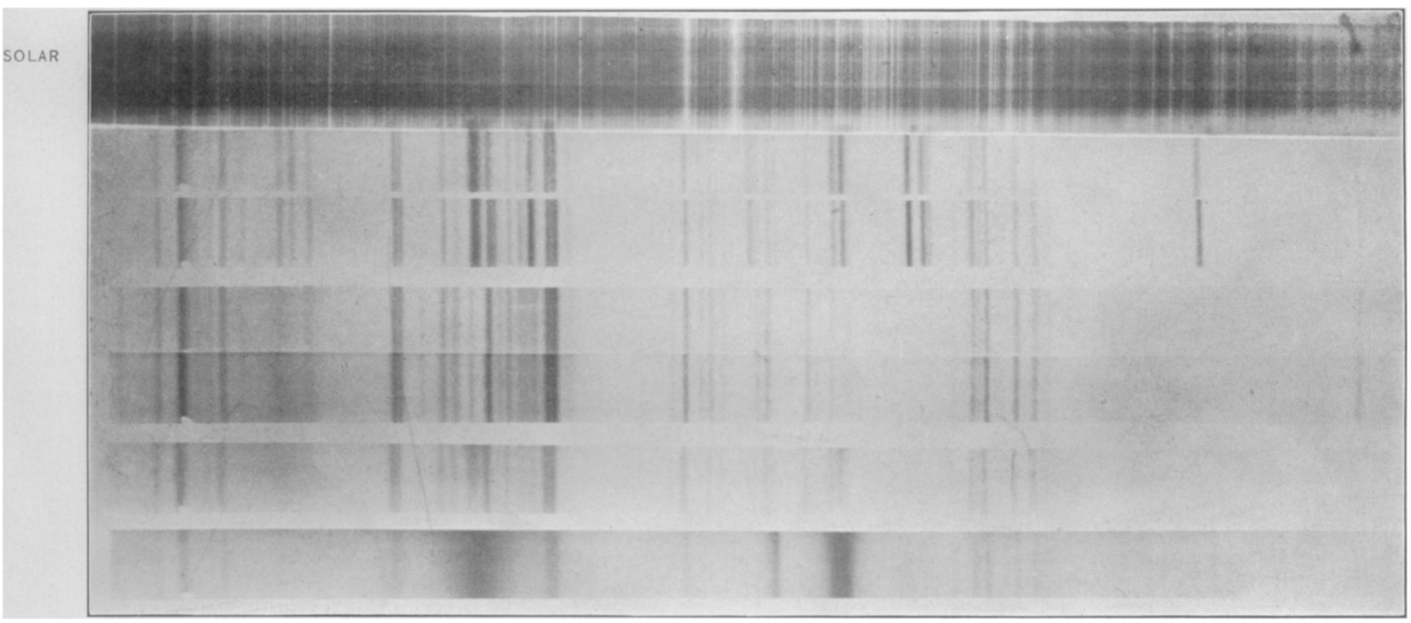

FIG. 10 (NEGATIVE)

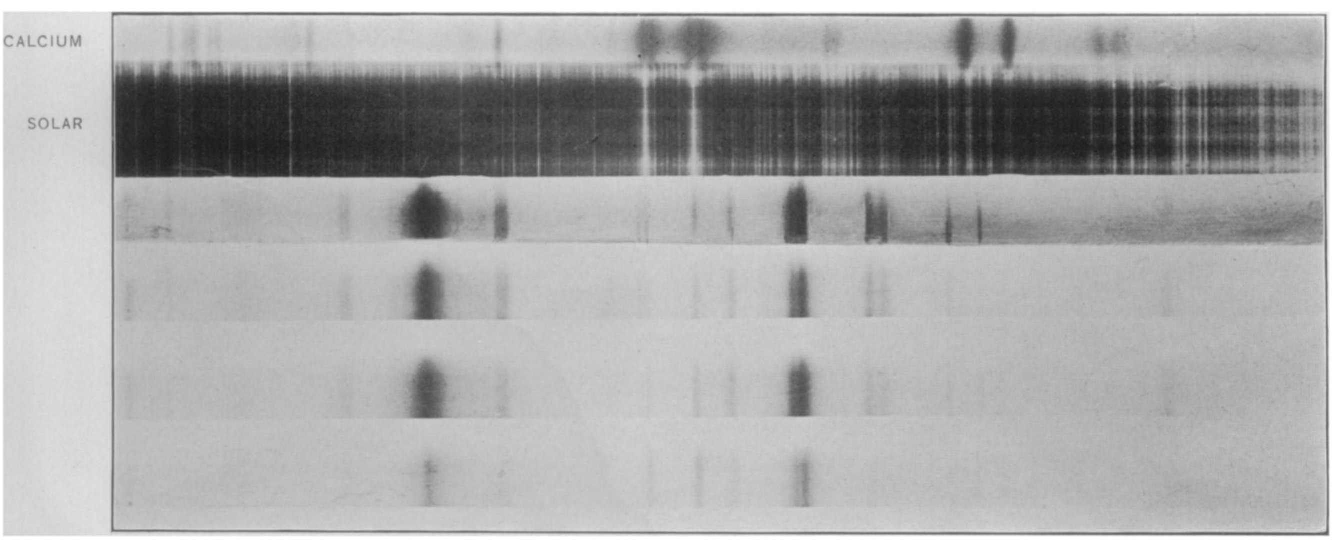

FIG. 11 (NEGATIVE)

TROWBRIDGE.—HIGH ELECTROMOTIVE FORCE